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CHARACTERIZATION OF CHAIN PILLAR STABILITY IN A DEEP WESTERN COAL MINE - CASE STUDY

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Abstract. Beginning in late 1985 and continuing through 1987, Bureau of Mines personnel investigated longwall chain pillar and entry design in two- and three-entry gateroad systems at a deep underground coal mine located in central Utah. To evaluate their respective stability characteristics, four chain pillars and two longwall panels within the two separate entry systems were instrumented with Bureau of Mines hydraulic borehole pressure cells to continuously monitor vertical and horizontal pillar and panel stresses through adjacent panel retreat. In addition, supplemental entry closure information was obtained from sites located in the vicinity of the instrumented pillars. The findings presented in this report demonstrate the practicality of evaluating mine pillar stability using in situ methods and support three significant conclusions regarding ground control aspects of the investigated two-entry system: (1) Total areal entry loading was considerably less for the two-entry system, as opposed to the three-entry system, (2) a smaller percentage of opened ground in the two-entry system contributed to a marked reduction in roof falls, and (3) lower areal loading in the two-entry system suggests improved ground conditions when mining the underlying seam.

Introduction

Adequate panel entry design with respect to mine safety, productivity, and resource recovery is of primary importance to underground coal producers. When designing longwall entry chain pillars, mine engineers must consider the varying degrees of support required during retreat mining of the adjacent panels to ensure adequate ventilation and the safe, uninhibited movement of mining personnel, coal, and materials. Acting as the primary tailgate entry support, chain pillars must contribute to entry stability for escapeway maintenance by shielding transferred panel loads and, as longwall retreat mining progresses, should yield to facilitate caving and total planned subsidence. Although other panel design parameters, such as panel geometry, orientation, and artificial support, may be altered to minimize potential ground control problems, these approaches may be expensive and often impractical, particularly when complicated by thick- and multiple-seam mining geometries. In comparison, varying chain pillar size and shape from panel to panel is relatively simple and often more cost effective.

To characterize entry stability with regard to varying chain pillar designs, a cooperative effort between the Bureau of Mines (BOM) and the Cyprus Plateau Mining Corporation (CPMC) was initiated to investigate gateroad conditions in two- and three-entry longwall systems at the Starpoint #2 Mine, Wattis, UT. Continuous pillar load measurements, utilizing Bureau-fabricated hydraulic borehole pressure cells (BPC's) installed across the critical dimension of the pillar (width), in conjunction with entry closure measurements and on-site observations, comprised the data base from which to compare the relative performances of the two panel entry systems. Although the entry systems investigated lie within the same coal seam and share a similar local geology and mining cover, chain pillar dimensions varied significantly: 15 m (50 ft) wide by 24 m (80 ft) long for pillars in the three-entry system, as opposed to 9 m (30 ft) wide by 26 m (85 ft) long in the two-entry system. The larger pillars appeared to behave as "stiff" structures, demonstrating abutment loading and maintaining a confined core throughout much of retreat mining. Conversely, the smaller pillars tended to yield progressively during first panel retreat as evidenced by rib unloading and accelerated entry closure with nearing face positions.

Though not presented in this report, the study also allowed BOM personnel to further refine previously developed techniques for quantifying the relationships between three-dimensional applied loads and pillar support capacity in the field (Lu, 1986) and for numerically modeling the behavior of a unique longwall mine design as a function of face position (Kripakov, 1986). The ultimate goal of such efforts is to provide the mining industry with integrated techniques for a wide range of mine design applications. At present, however, it is our intent to solely describe the stability characteristics of two different entry systems subject to similar environmental conditions.

Background

A variety of pillar design techniques have been developed over the past several decades to eliminate sudden premature ground failures and associated safety hazards and reserve losses, particularly in the highly loaded abutment zones surrounding retreat mining operations. Empirical formulas relating sample size and shape to pillar strength have attempted to incorporate standardized laboratory testing as a basis for pillar design (Holland, 1964; Bieniawski, 1968; Hustrulid, 1976; Obert, 1967; Gaddy, 1956). Panek (1980) extended this approach using classical similitude analyses to include not only the geometry of the model pillar, but also the structure of the coal, orientation and frequency of discontinuities, and roof and floor relative confinement effects. Babcock (1984) has since expanded greatly on our understanding of the role of pillar end constraint, analyzing various roof-pillar-floor modulus ratios, pillar geometries, and the effects of the presence of pressurized gas. Taking a slightly different approach, Salamon and Munro (1967) reported on more than 100 cases of both failed and stable pillars during a survey of coal collieries in South Africa, representing one of the few quantitative statistical studies relating unit coal strength and pillar geometry to observed field conditions. Wilson (1972) and Grobbelaar (1970) initiated a departure from all laboratory extrapolation methods by devising the now popular "confined core" concept of pillar characterization. This represented one of the first attempts to determine the effects of stress redistribution between openings in ground given a specific in situ stress state and various pillar intact rock properties. Refinements in this approach have endeavored to incorporate the work of previous researchers, particularly in the areas of roof and floor confinement and the post-yield characteristics of the pillar ribs. Disregarding the need to design pillars to necessarily support large overburden loads, Wardell and Eynon (1968) and Serata (1982) proposed the utilization of stress control through pillars designed to yield upon development. Upon yielding, the overburden stress diverts to the adjacent abutment structures, thereby requiring the pillars to support the dead load remaining beneath the newly formed "pressure arch." Furthering their work, Maleki et al. (1987) proposed preliminary guidelines for longwall gate design using yield pillars. Although this approach to pillar design deserves further study, the flexibility for widespread underground application has yet to be demonstrated in deep western coal mines.

All of the aforementioned design methods have inherent limitations. As a result, rule-of-thumb estimates and acquired experience remain the preferred means of pillar design practiced in the United States today. Among these limitations are the following:

1. The nonconsideration of cyclic and irregular pillar loading when estimating the term of pillar stability.
2. The noninclusion of fatigue-related material failure criteria for intact coal subjected to <u>sustained</u> loading less than the laboratory determined dry failure strength, whether they be cyclic or static loads.
3. The inability to accurately characterize pillar applied loads in situ for various stages of mining, particularly nonsymmetrical loads occurring in abutment regions or as influenced by multiple-seam workings.
4. The inability to portray pillar post-yield effects on stress redistribution about adjacent entry systems.

For numerous site-specific conditions, the previously mentioned methods have provided good estimates for production pillar design; i.e., those pillars required to support typically static loads up until final extraction. As mines have gone under greater cover and the diversity of pillar environments has increased with the advent of new mining methods, "stiff" pillar designs have suffered escalating burst activity and have helped generate adverse stress conditions responsible for the initiation of cutter roof and severe floor heave. "Yield" pillar designs, on the other hand, may provide an attractive alternative, saving potentially sterilized reserves and reducing excessive development times, while proving to be an acceptable means of stress control, particularly in longwall applications. Since no reliable method now exists to determine the pillar-time-to-yield or the load-carrying capacity of variably yielded pillars, field monitoring of pillar loads is a logical approach for determining stability characteristics from the onset of development through final panel extraction. Therefore, this was the approach taken to compare two separate pillar and entry systems at the Starpoint #2 Mine.

In keeping with Federal regulatory requirements, CPMC mined the first three adjacent longwall panels in the Wattis seam utilizing three-entry headgates (Figure 1). Geotechnical data collected during initial panel extraction, combined with computer-aided numerical analyses, provided the basis from which the mine petitioned for variance to operate retreat mining sections with two-entry configurations, employing chain pillars of significantly reduced width (Maleki, 1986). This was done to achieve improvements in three critical areas (Maleki, 1987):

1. A reduction in geology-related roof falls by limiting the amount of ground area affected by entry system development.
2. A reduction of total ground stress about the entries due to a corresponding reduction in the pre-panel extraction tributary-area-load.
3. The elimination of concentrated load transfer to future mining operations in the underlying seam through the use of yield pillar designs.

Demonstrating their commitment to improved mine design, CPMC mine management afforded Bureau personnel the opportunity to (1) assist in their evaluation of two radically different entry systems subjected to nearly identical mining conditions, and (2) expand this investigation to multiple-seam applications in the future. The chain pillar stability portion of this study, reported herein, was initiated in late 1985 and concluded in mid-1987.

General Approach

The approach taken to investigate chain pillar and associated gateroad stability, at CPMC's Starpoint #2 Mine, combined in situ ground pressure and entry closure monitoring with laboratory physical property measurements and compatible numerical modeling techniques. By themselves, each design technique has its merits along with its weaknesses; together they build upon their strengths to become a sophisticated and powerful design methodology. Field studies reveal the time-related characteristics of the in situ mining environment. Laboratory investigations assist in the development of criteria that describe the various modes of failure experienced in the field. Numerical modeling incorporates field and laboratory findings to "calibrate" analytical descriptions of the mining process, which, in turn, alert the mine planner to potentially hazardous conditions in future workings. Although all three techniques independently suffer various limitations, continued research into data acquisition methods, "true" triaxial coal strength

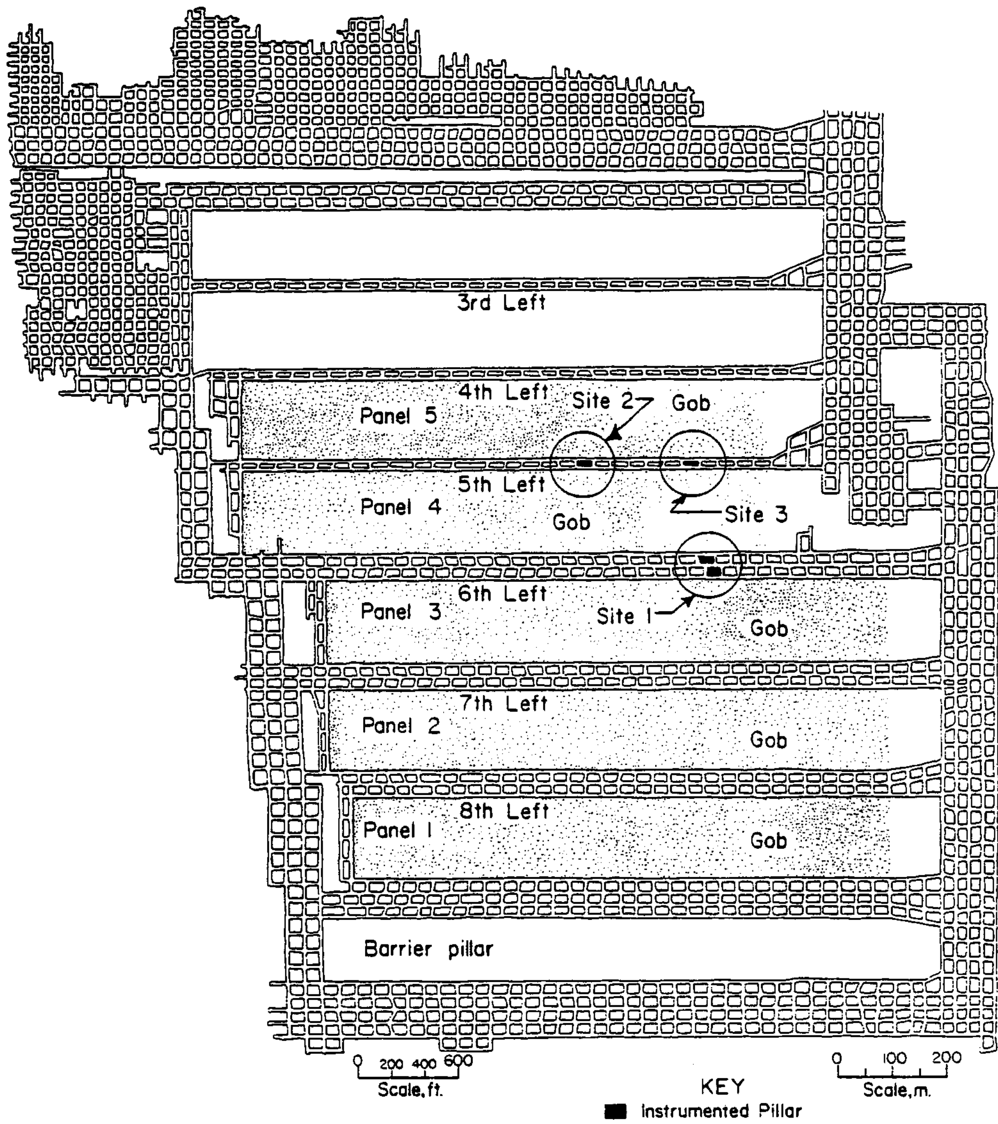

Figure 1. Study site locations at Starpoint No. 2 Mine, Cyprus Plateau Mining Corp., Wattis, UT.

determinations (Lu, 1986), and various modeling refinements should result in a sound, experience-proven system of mine design available to the industry.

To better assist the immediate needs of the coal mining industry, conclusive qualitative aspects of the field investigation are presented at this time. Pending completion of related laboratory and numerical studies, a more comprehensive analysis of the CPMC two- versus three-entry investigation is forthcoming.

Site Investigation

Located approximately 40 km (25 mi) southwest of Price, UT, CPMC's Starpoint #2 Mine lies along the eastern edge of the Wasatch Plateau; a north-south elongate physiographic province of Central Utah, sandwiched between the Basin and Range and Colorado Plateau provinces. The strata of the Plateau are primarily composed of Upper Cretaceous Mesa Verde-group units, dipping 2° to 3° southeastward. Within the coal property, three mineable seams exist; the Wattis, Middle, and Hiawatha, listed in descending order. The Wattis and Middle seam interburden averages 14 m (45 ft), with 20 to 27 m (65 to 90 ft) lying between the Middle and Hiawatha seams (Maleki et al., 1987). Mining cover over the Wattis seam study sites averages 460 m (1,500 ft).

A thinly bedded to massive lower coastal plain mudstone, containing variable amounts of silt and a significant amount of carbonaceous material (~10%), comprises a majority of the immediate roof in the Wattis seam. Laboratory testing of core retrieved from near the test sites indicated a trend of increasing compressive strength with depth into the roof; however, zones of weakness were common. Degradational-style sandstone channels cutting into the immediate roof represent the major discontinuity found in the Wattis seam, and appear to be widespread across the panels mined during this investigation.

While the channels do not displace the seam, oriented fracture sets and stress concentrations have been reported to significantly reduce localized roof stability (Maleki et al., 1987). This is evidenced by a higher frequency of roof falls concurrent with channel/entry intersections.

During the investigation, three instrumentation sites were established in the longwall retreat operations in the Wattis seam (Figure 1). Site 1, located in the 6th Left three-entry gateroad system, included two adjacent 15 m wide (50 ft) chain pillars and a 15 m (50 ft) portion of longwall panel #4. Sites 2 and 3 were located in the 5th Left two-entry gateroad system with both consisting of an instrumented 9 m wide (30 ft) chain pillar and 15 m (50 ft) portion of longwall panel #5. BOM-fabricated hydraulic borehole pressure cells, developed by Panek and Stock (1967), were employed at each of the sites to determine (1) the onset of abutment loading with face advance, and (2) a profile of vertical load distribution across the panel and entry system with longwall face position. Clock-wound, hydraulic chart-type recorders continuously monitored cell pressure changes during all stages of mining. Supplemental information was obtained from coring and roof sag and entry closure measurements taken in the vicinity of the instrumented pillars. Detailed instrumentation plans are shown in Figures 2 and 3. Site 2 is representative of Site 3 as well.

Occasional pressure cell failures, not necessarily due to excessive loading, and the inability to access closure stations regularly made it difficult to assess entry and pillar stability characteristics quantitatively. However, trends in the data coupled with personal observation provide a good base from which to evaluate qualitatively the behavior of the two- and three-entry systems.

Data Analysis

To compare the stability characteristics for each of the study sites, six convenient face positions were chosen; five for the first panel retreat and one for second panel mining. The

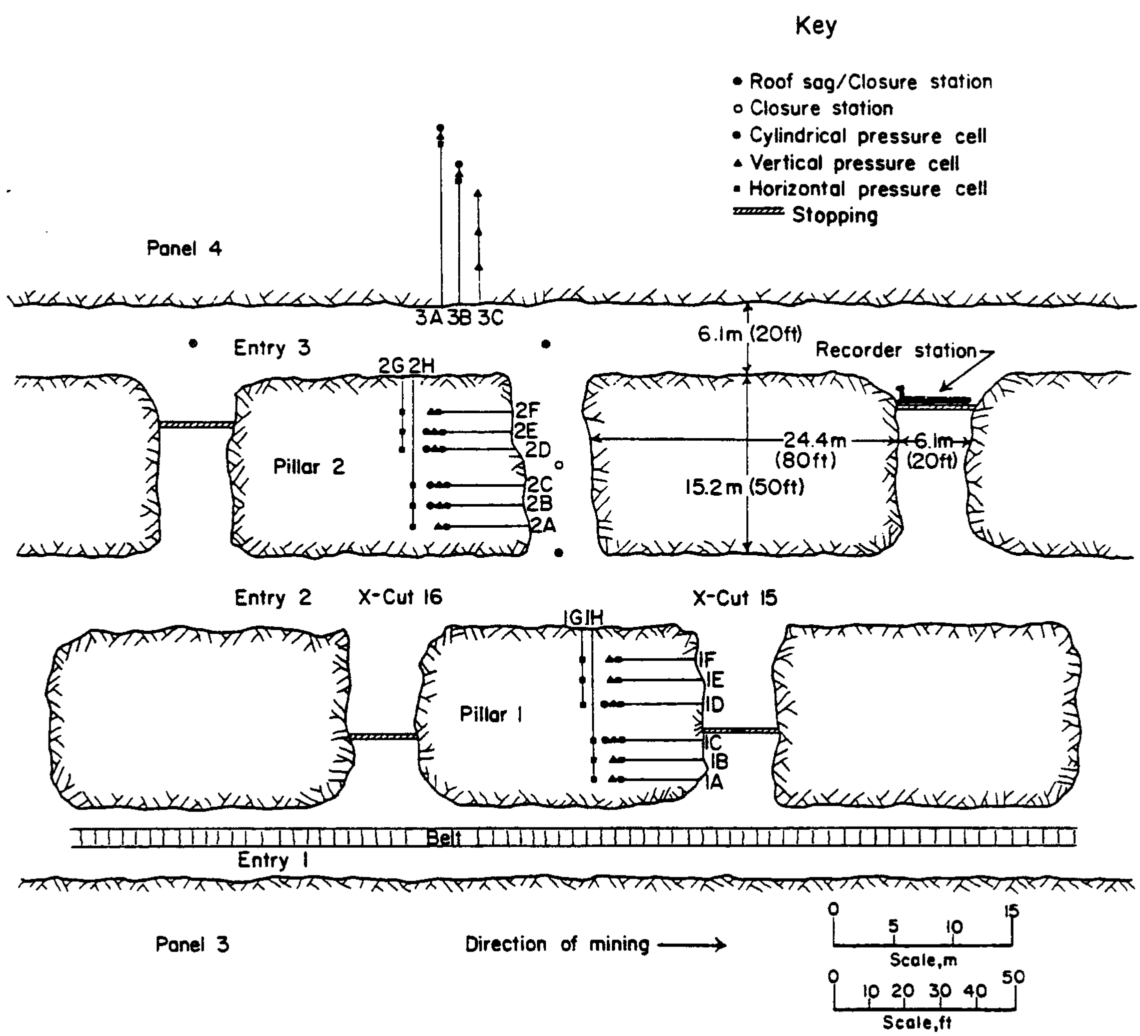

Figure 2. Detail of three-entry instrumentation plan.

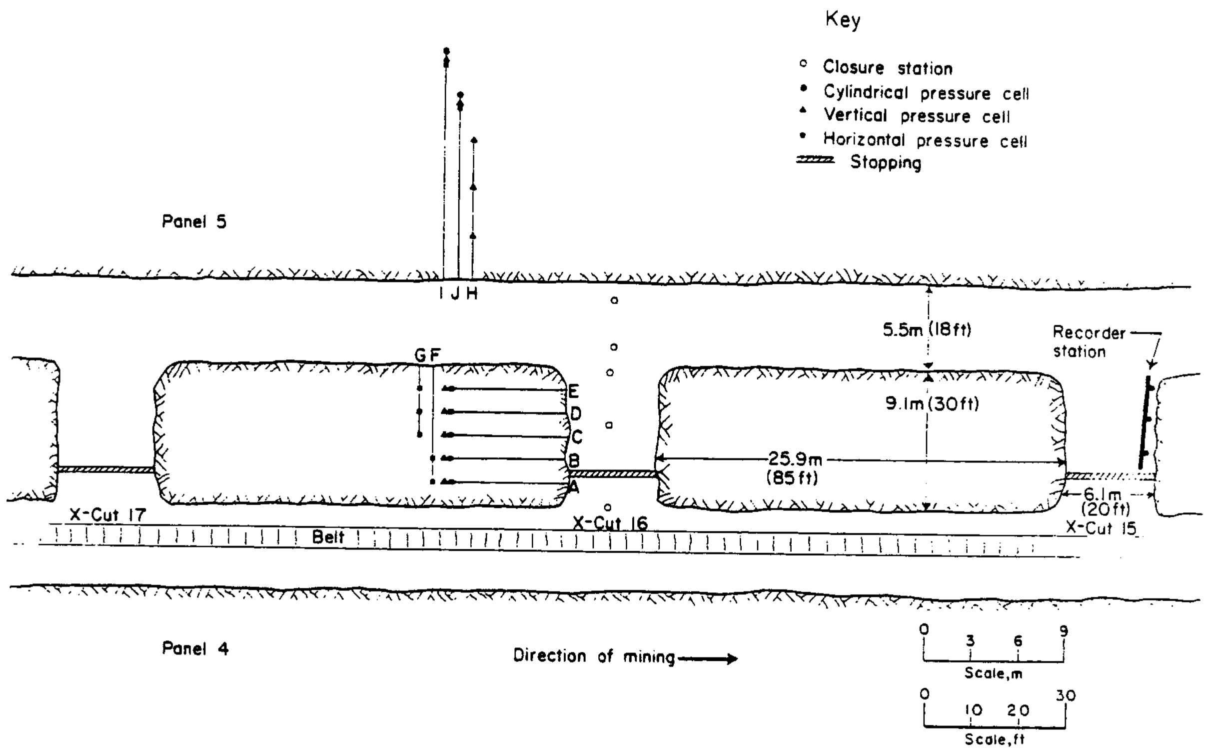

Figure 3. Detail of two-entry instrumentation plan. (The plan is identical for Sites 2 and 3.)

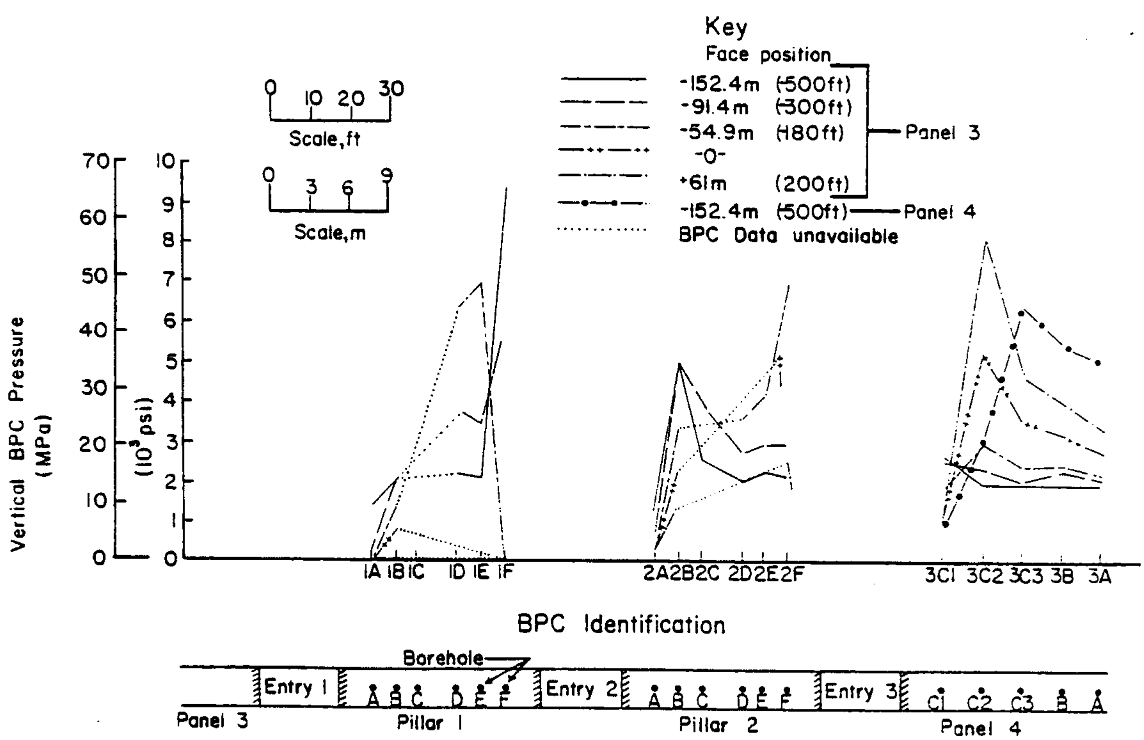

Figure 4. Pressure profiles, looking inby, for Site 1 at various panel 3 and panel 4 face positions.

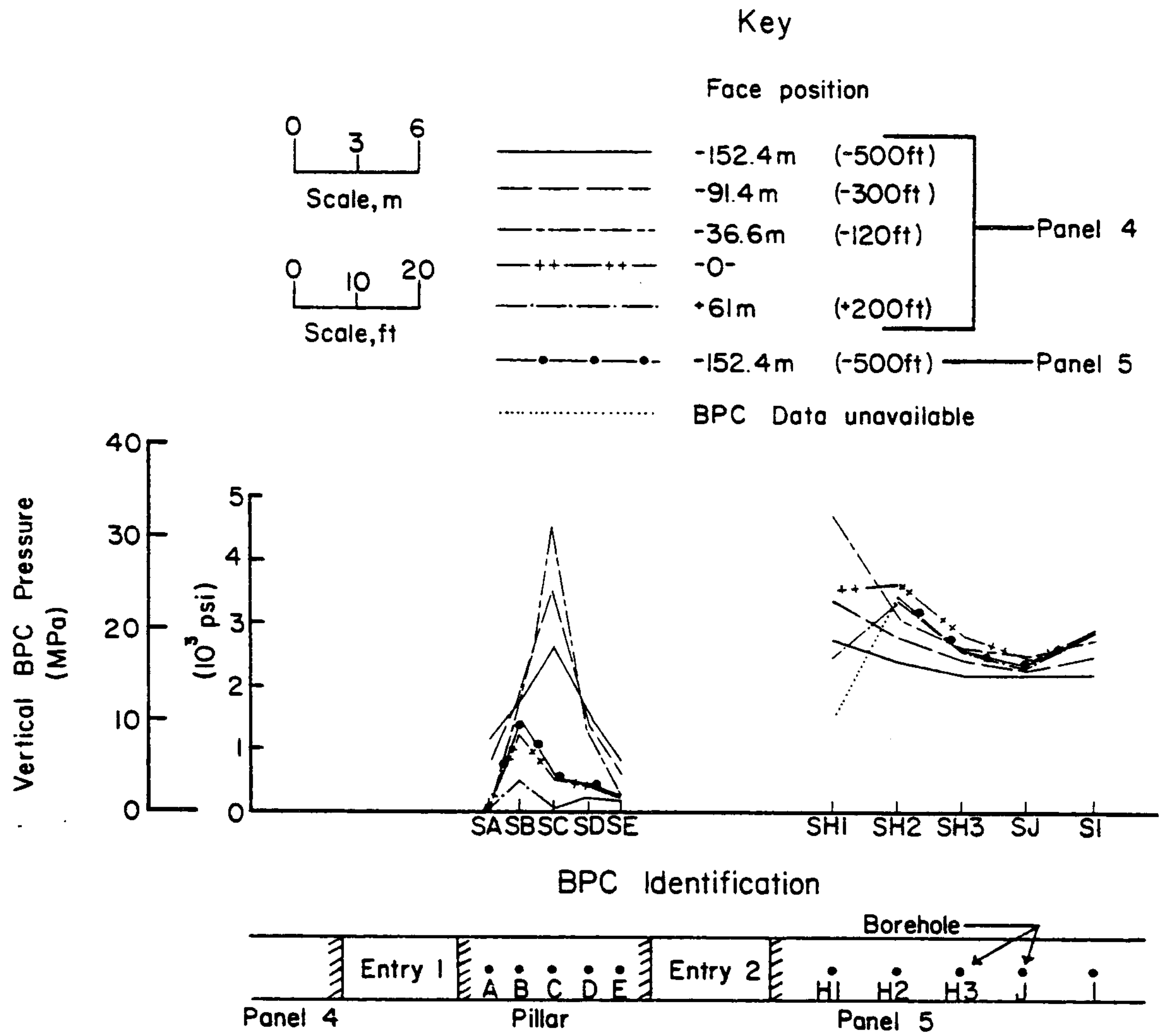

Figure 5. Pressure profiles, looking inby, for Site 2 at various panel 4 and panel 5 face positions.

lone face position chosen for second mining is due to (1) pressure cell failures at Site 1 making it difficult to interpret the data at face positions closer than -152 m (-500 ft), and (2) total pillar pressures did not radically change within this face distance for Sites 2 and 3. (Note that - indicates inby, and + outby.) In addition, these face positions correspond to stages in the mining sequence presently being analyzed using novel numerical modeling techniques.

Figures 4, 5, and 6 depict the loading histories for the instrumented sites. It should be noted that the presented BPC data are unrefined; i.e., have not been reduced in terms of absolute ground stress (Lu, 1986), and serve as the primary basis for the following qualitative interpretation.

Site 1

- Although unexplained pressure cell failures occurring within the pillars hindered complete BPC data collection, vertical pressure data for the first three face positions for panel #3 appear to indicate progressive rib failure occurring in pillar 1, with associated load being transferred to pillar 2 and solid coal of panel #4 (Figure 4). Data for the three remaining face positions are inconclusive for pillar 1; however, cells A, B, and F in pillar 2 indicate diminished rib loading, suggesting a narrowing of the confined core. Supplementary horizontal BPC data (not shown) support the analysis through the -55 m (-180 ft) face position. Unfortunately, data collection was not possible beyond this point in the mining sequence.

- The loading sequence of longwall panel #4 explains a great deal of the behavior observed in the entry pillars during the extraction of panel #3. For the first face position, -152 m (-500 ft), panel #4 simply experiences the presence of the adjacent opening(s). As the face reaches -91 m (-300 ft), fluctuations in cell response signal the approaching face abutment. At -55 m (-180 ft), rib failure, and resulting pillar core narrowing, in conjunction with the approaching face abutment, causes a load shift to panel #4, enhancing the development of a yield/abutment zone in the first 6 m (20 ft) of panel. When first panel retreat pulls even with the site instrumentation (face position -0), loss of pillar load-bearing capacity is further evidenced by a marked increase in the abutment zone magnitude and overall panel load. Continued deterioration of pillar load-bearing capacity, once the longwall has passed, provides for additional side abutment loading, as observed at the +61 m (200 ft) face position. Finally, when the panel #4 face is at -152 m (-500 ft), the peak abutment load has shifted to approximately 9 m (30 ft) within the panel, with relatively high loads continuing at least 6 m (20 ft) further into the panel. It is likely that while the entry pillars have yielded to a large degree, their combined load carrying capacity, in terms of peak and residual strength, remains sufficient to hold the intermediate and/or main roof intact, allowing the majority of mined-panel loading to cantilever to panel #4. In turn, the prolonged high areal loading, and associated entry closure (Figure 7), provide for a greater probability of immediate roof instability, as well as associated face problems when extracting panel #4.

Site 2

- After a brief inspection of the vertical BPC data (Figure 5), it becomes clear that the 9 m wide (30 ft) pillar used in this entry system began yielding during or shortly after development. The pillar core is confined to the central 3 m (10 ft) of the pillar and retains appreciable load-carrying capacity until longwall #4 is even with the instrumentation. Progressive pillar failure and accompanying load transference continue to decrease total pillar loading as the panels advance. Horizontal BPC data (not shown) confirm core development and indicate an apparent loss of pillar confinement at -0 m face position.

- The panel #5 loading sequence correlates with that of the adjacent chain pillar; however, it is not as evident as at Site 1. Increased areal loading, to a panel #4 face position of-37 m (-120 ft), generates a near-rib abutment peaking around 34.5 MPa (5,000 psi) gage pressure. As the face pulls even with the instrumentation and advances beyond, the abutment shifts into panel #5 approximately 3 m (10 ft), with corresponding redistributions of load occurring deeper in the panel. In comparison, the total integrated load across the instrumented sites after first panel retreat is less for the two-entry than for the three-entry system. Total gate width may account for this difference.

Site 3

- The chain pillar in this situation did not undergo the higher loading observed at Site 2. This may be explained by the presence of a sand channel in the proximity of the Site 2 instrumentation. The greater relative stiffness of the channel may have served to concentrate

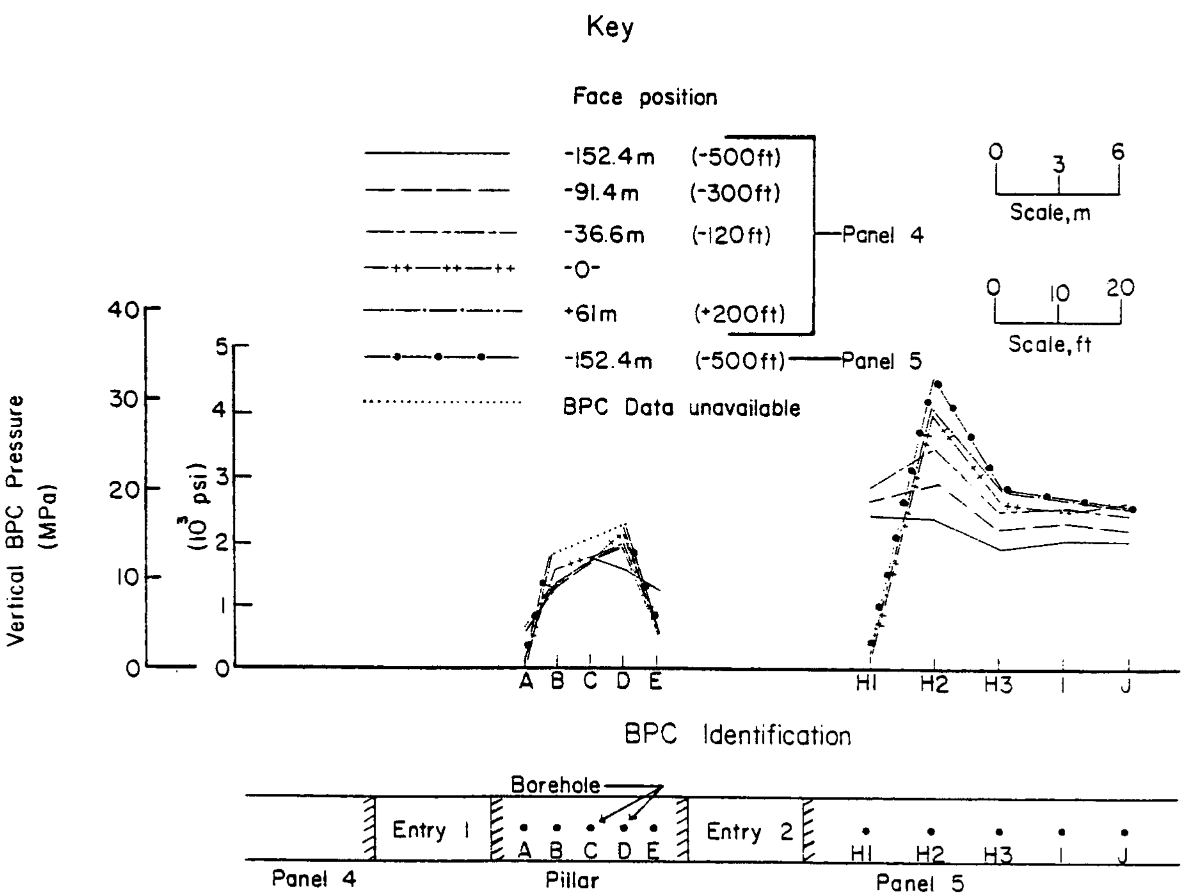

Figure 6. Pressure profiles, looking inby, for Site 3 at various panel 4 and panel 5 face positions.

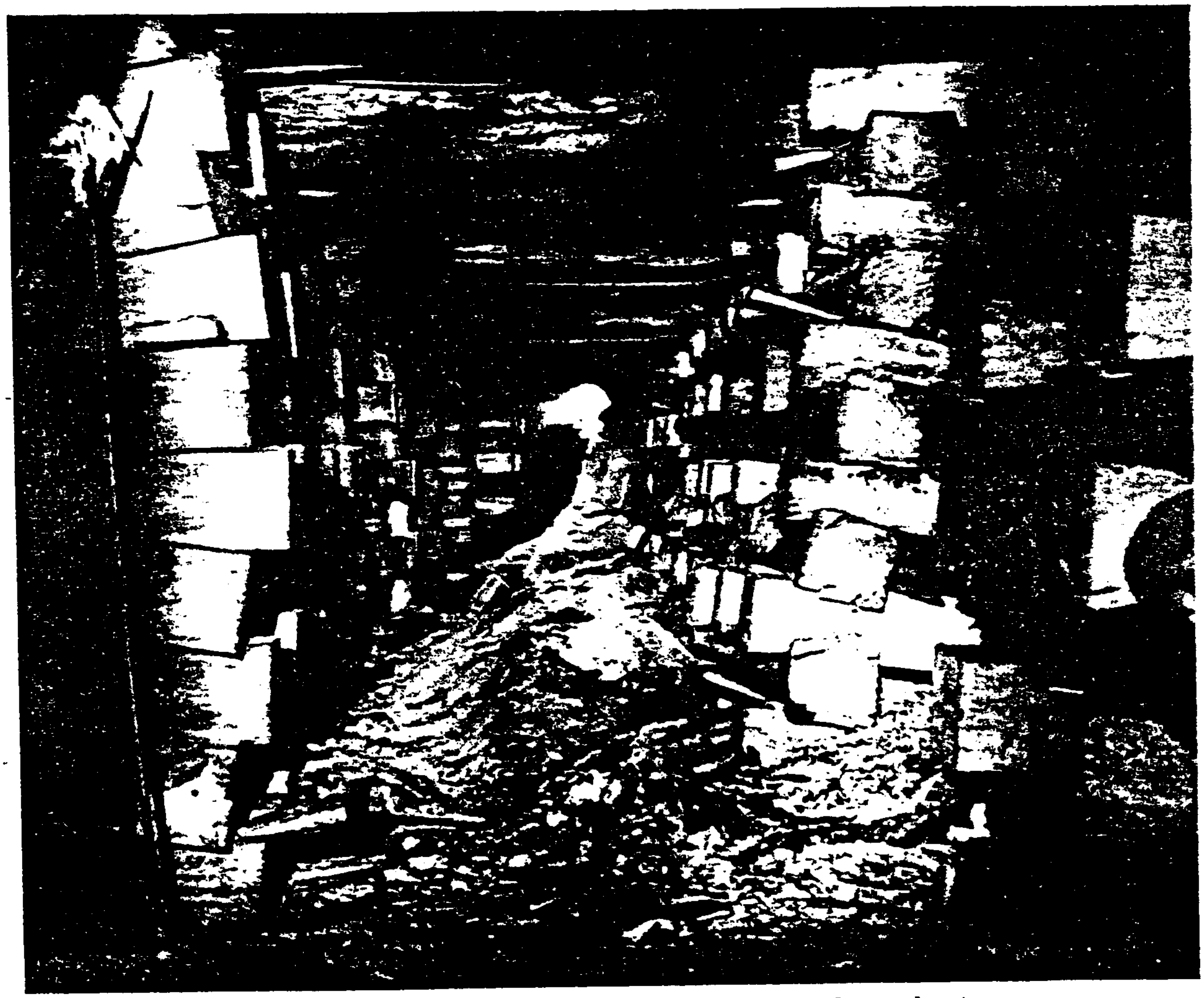

Figure 7. Excessive floor heave occurring in 6th Left panel entry.

load more effectively prior to first face retreat beyond the site. In any case, (Figure 6) the pillar core at Site 3 is well defined and changes little with face position. Vertical and horizontal BPC failures in hole C preclude a detailed interpretation of pillar behavior after panel #4 advances beyond the site; however, loading trends of the remaining cell combinations suggest little change in the pillar-loading profile.

Although the panel-loading profile is more distinct than that for Site 2, load transference from the pillar to the panel is not as apparent. Total panel loading appears to increase with the advancing of panel #4. The actual percentage increase may be greater than that depicted depending on the exact location and magnitude of the peak abutment between cell locations H1 and H2. At -0 m, the peak has obviously shifted into the panel even further; however, little or no change in total panel loading is observed (evidenced by the area under the respective profiles). This continues to hold true once the face has passed. Also, total areal loading remains significantly less than that experienced in the three-entry system at Site 1.

Clearly each of the sites exhibits unique load profile characteristics, yet notable dissimilarities exist between the two panel entry systems. First, total and peak panel and pillar loads across Site 1 are often twice those measured at Sites 2 and 3 for similar face positions. Observed entry conditions tend to support these findings (Figures 8 and 9). Secondly, the distribution of loads is predominantly pillar-controlled in the 6th left three-entry system, switching to panel-controlled with the passing of the first panel, whereas measured pillar loads never exceed peak panel loads in the 5th Left two-entry system. This qualifies the "stiff" and "yield" interpretations presented earlier and clearly shows the relative loading magnitudes the entries experienced during panel retreat operations. Lastly, significant increases in panel loading are confined to the first 12 m (40 ft) of the instrumented panel in the two-entry system, yet extend considerably beyond 15 m (50 ft) for the three-entry system. It was not determined to what extent this affected face-cutting operations. Also, the apparent depth of the panel yield zone is 50% greater for the three-entry system. This would appear to be a direct indicator of the relative load transference for a 20 m wide (66 ft) gate (Sites

Figure 8. Heavily timbered 6th Left panel entry shows signs of progressive deterioration due to sustained loading.

2 and 3) versus that for a gate width of 47 m (154 ft) at Site 1.

Concurrent with the pillar investigation, entry closure measurements were recorded to supplement pressure cell results for the three sites. Collection of closure data at Site 1 was not initiated until panel #3 was immediately adjacent to the instrumentation; consequently, the closure history is incomplete (Figure 10). An attempt was made to project the total closure curves, obtained for Site 1, back to a -152 m (-500 ft) panel #3 face position; what appears to be a common position for the onset of front abutment loading. Based on initially measured closure rates, the extrapolated maximum roof-to-floor convergence was approximately 20 cm (8 in) in the center entry, with 9 cm (3.5 in) of closure occurring in the tailgate crosscut. A more complete history was obtained at Sites 2 and 3 in the 5th Left panel entries (Figures 11 and 12). For both sites, the onset of the panel front abutment load began around the -152 to -183 m (-500 to -600 ft) panel #4 face position, with noticeable increases in rate occurring at -61 m (-200 ft) and again inside -31 m (-100 ft). This correlates qualitatively with the pressure profiles generated for Sites 2 and 3; as pillar pressures drop, and/or panel abutments shift deeper into the solid coal rib, closure rates increase.

Roof sag data indicated similar trends in rate increases at the aforementioned face positions (Figure 13). The maximum total measured sag for the three sag stations at Site 1 barely exceeded 1 inch during the first panel retreat monitoring period, indicating a majority of entry closure was due to floor heave. Roof sag information was not collected at the 5th Left sites.

Conclusions

Although difficulties experienced with data acquisition make quantitative interpretations of the findings uncertain, qualitative analyses, primarily based on the mining of panels #3 and #4, indicate that the goals of CPMC's mine management, from a ground control viewpoint, were perhaps realized in switching from three- to two-entry longwall panel access systems at the Starpoint #2 Mine:

- Combining a yield pillar design with a 57% reduction in gate width effectively reduced total areal loading throughout the various stages of retreat mining.

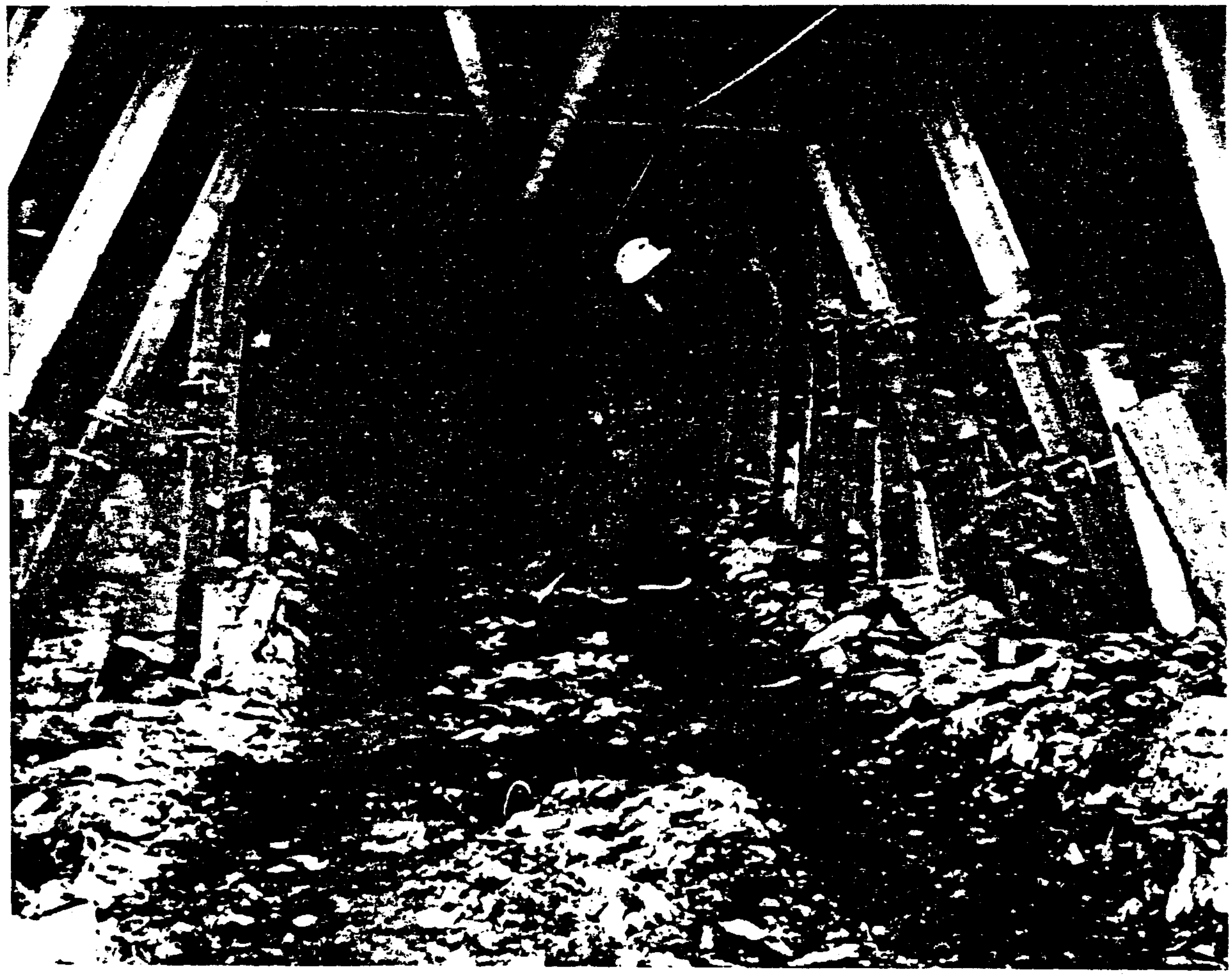

Figure 9. Serving as the panel 5 tailgate, this 5th Left entry shows no signs of excessive loading, remaining open the entire distance to the face. (The modified yielding arches served as adequate replacements for traditional timbering.)

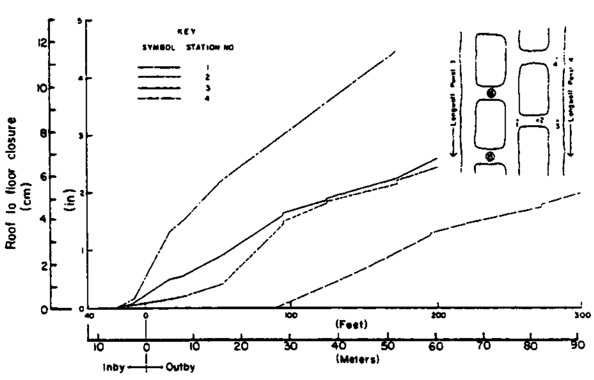

Figure 10. Entry closure data for Site 1.

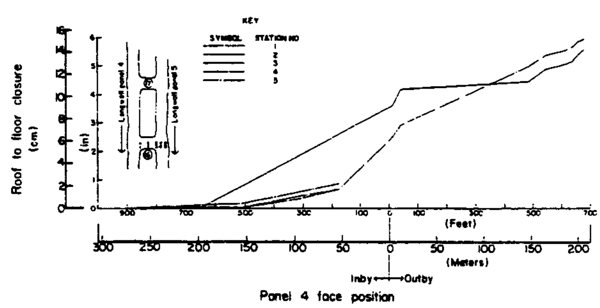

Figure 11. Entry closure data for Site 2.

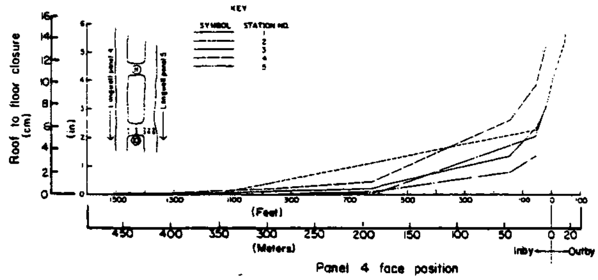

Figure 12. Entry closure data for Site 3.

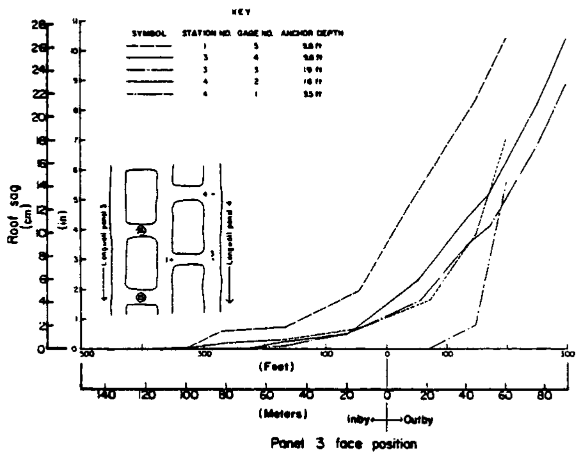

Figure 13. Roof sag data collected during panel 3 extraction for Site 1.

- According to a mine representative, a smaller percentage of opened ground in the 5th Left two-entry system resulted in a marked reduction in roof falls, although it was reported these entries possessed a higher overall percentage of geologically disturbed roof than those in the 6th Left gate (Maleki, 1987).

- The lower magnitude, more evenly distributed loads across the 5th Left test sites suggest improved ground conditions may be encountered when mining the nearby underlying seams.

Additionally, lower average loads distributed over a much reduced area benefit CPMC's roof control efforts when faults, sand channels, and fracture sets are encountered during entry development. Lower loads do not concentrate along channels or promote localized fracture propagation as readily, and the smaller gate width more effectively transfers load to the adjacent abutment structures.

Recommendations for future work in this and similar areas of study include improving methods for long-term ground pressure monitoring in deleterious mining environments and extending this technology to characterize pillar behavior in the gob to afford a better understanding of seam interaction relationships.

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